good agreement, are not consistent with respect to the very weak oscillations in their angular distributions.

VI. CONCLUSIONS

The results of analysis of the new data at 15 MeV are consistent with those discussed in paper 1. The previously observed trend of the parameters to vary smoothly as a function of A was again observed with a few exceptions. We are reluctant to put much weight in the departures of the real well-depth behavior from the trend in some cases, since they resulted from very small oscillations in the data.

PHYSICAL REVIEW VOLUME 134, NUMBER 2B 27 APRIL 1964

Scattering of Polarized 3.25-MeV Neutrons by Medium Weight Nuclei*†

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(Received 6 December 1963)

The polarization produced in the 90° elastic scattering of 3.25-MeV neutrons from Fe, Ni, Co, Cu, Zr, and Mo was measured. The $\mathrm{D}(d,n)\mathrm{He}^3$ reaction was used as a source of partially polarized neutrons to determine the scattering asymmetry. The variation of the measured values with the atomic weight indicates a resonance structure similar to that observed by Clement *et al.* at 380 keV but with the polarization ranging from approximately -0.5 to $+0.4$. In addition, polarization measurements of neutrons scattered by C and W were performed.

INTRODUCTION

SYSTEMATIC measurements[1–6] of the elastic scattering of polarized neutrons by medium and heavy weight nuclei have been performed in the 0.4- to 2.1-MeV energy range by several workers for comparison with optical model predictions. Theory is not in good agreement with the results of these experiments. That some disagreement might exist at low energies is not unexpected since fewer levels of both the compound and residual nucleus are involved. The latter condition increases the compound elastic scattering, especially for the lighter of these nuclei.

At higher energies (e.g., 14 MeV) it is possible to fit neutron angular distribution and total cross-section data with a Bjorklund-Fernbach optical-model potential.[7] The inclusion of a spin-orbit coupling term into this potential is necessary in order to yield the correct large-angle scattering. However, the magnitude of this term is not sensitive to the angular distribution and can best be determined by the polarization. This has been shown in the case of 24-MeV neutrons by the work of Wong *et al.*[7] For proton scattering, where many polarization data are available, good agreement is attained[8] for energies above a few MeV.

The neutron polarization data[9–14] for $2.1<E_n<14$

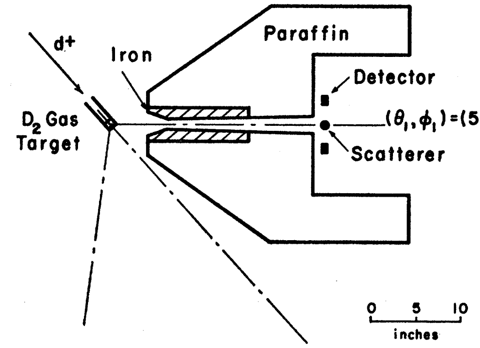

FIG. 1. Experimental arrangement for 90° scattering angle, showing the horizontal cross section view of the collimator.

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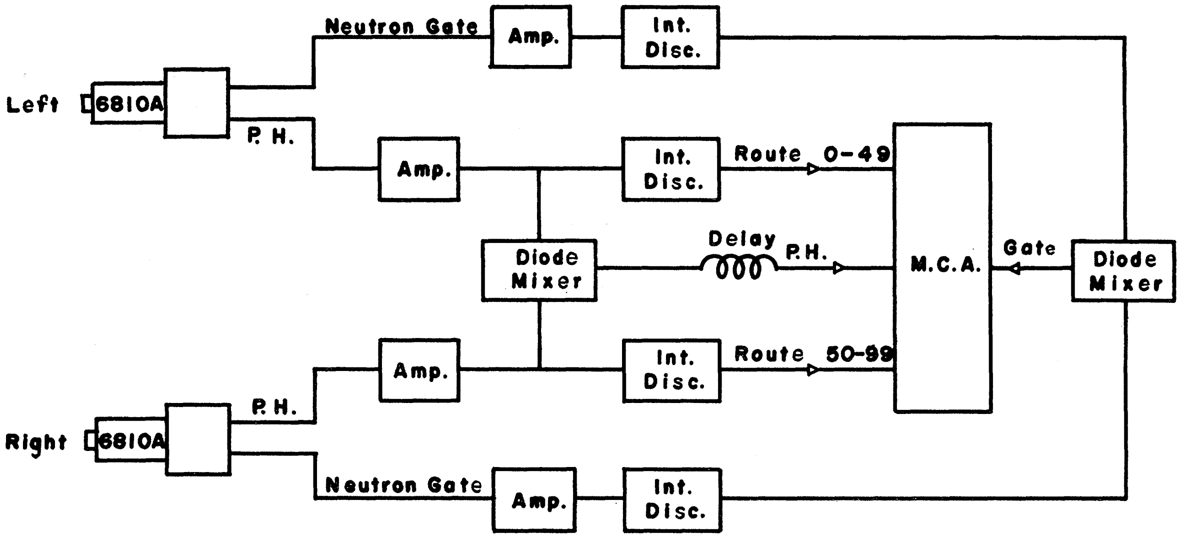

FIG. 2. Block diagram of electronics.

MeV are insufficient for systematic comparison with the optical model, and it was therefore decided to provide further data at 3.25 MeV. The results at lower energies indicate that it would be of interest to measure the polarization at 90° scattering angle for various mass numbers in the region from 50 to 100: optical-model calculations[3] suggest that the structure observed below 1 MeV in the vicinity of $A=100$ be interpreted in terms of giant *p*-wave resonance splitting[15]; Cranberg,[4] however, finds a similar structure unshifted in A at 2.08 MeV and a strong contribution of *d*- or higher order waves; at 90° this structure is more pronounced. Measurements at this angle are reported here for Fe, Ni, Co, Cu, Zr, Mo, and W.

For spin-$\frac{1}{2}$ particles of polarization $\mathbf{n}_1 P_1$ incident on an unpolarized target, the differential cross section for elastic scattering is given by[16]

$$\sigma(\theta,\Phi)=\sigma_0(\theta)(1+P_1P_2\mathbf{n}_1\cdot\mathbf{n}_2), \tag{1}$$

where

$$\mathbf{n}_2=\mathbf{k}_i\times\mathbf{k}_f/|\mathbf{k}_i\times\mathbf{k}_f|,$$

and $\sigma_0(\theta)$ and $P_2(\theta)$ are the differential cross section and induced polarization, respectively, for the case of an unpolarized incident beam. $P_2(\theta)$, therefore, can be inferred from P_1 and the measured "left-right" scattering ratio, $r=\sigma(\theta,0)/\sigma(\theta,\pi)$, by the relation

$$P_1P_2=(r-1)/(r+1). \tag{2}$$

EXPERIMENTAL METHOD

The $D(d,n)$ He^3 reaction was used in the experiment as a source of partially polarized neutrons. A 1.0-MeV deuteron beam passed through a 200-keV-thick foil into a 400-keV deuterium gas target. The neutrons emitted at 50° (laboratory system) with respect to the incident deuterons were distributed in energy from 3.05 to 3.40 MeV with an average energy of 3.25 MeV. The average neutron polarization inferred from Pasma's smooth curve[17] for $P_1(E_d,48°)$, which represents the thin-target measurements of several workers,[17–19] is -0.11. However, more recent measurements[20,21] of $P_1(E_d,\theta)$ for $E_d<200$ keV are in disagreement with a previous result[16] at $E_d=200$ keV and imply a more negative value for the average polarization; e.g., -0.125 is obtained if, for $P_1(E_d)$, a straight line connecting Kane's result[20] to the thin-target data of Levintov *et al.*[19] is assumed. A still higher value is indicated by the thick-target measurements of Levintov *et al.*,[19] which show significantly larger polarizations for $0.4<E_d<0.8$ MeV than Pasma's results and are consistent with an average polarization of approximately -0.13 to -0.15 for this energy range. The relative values of P_2 presented here are not affected by the uncertainty in P_1 since all measurements were identical in respect to incident neutrons.

The experimental apparatus is shown in Fig. 1. The $D(d,n)He^3$ neutrons emitted at 50° were incident on cylindrical scattering samples. Two similar stilbene scintillators (1-in. diam.$\times\frac{5}{8}$ in.), placed in the plane of the target reaction and shielded from the direct flux of neutrons from the target, detected the 90° (laboratory system) scattering events to the "left" and "right." The scatterer was $2\frac{5}{8}$ in. from each detector. The spectra were simultaneously recorded in two subgroups of a

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TABLE I. Summary of experimental results for $E_n = 3.25$ MeV and 90° laboratory scattering angle.

Element	Dimensions of scatterer (in.): Diameter	Length	$(-P_1P_2)$
Fe	1.00	2.14	$+0.0208 \pm 0.0047$
Ni	1.00	2.00	$+0.0299 \pm 0.0048$
Co	1.00	2.00	$+0.0328 \pm 0.0044$
Cu	1.00	2.13	$+0.0439 \pm 0.0058$
Zr	0.97	1.99	-0.0544 ± 0.0042
Mo	0.96	1.94	-0.0552 ± 0.0047
W	1.00	2.13	$+0.0018 \pm 0.0041$

multichannel pulse-height analyzer as shown in Fig. 2. The inelastically scattered neutrons associated with levels of the residual nucleus greater than 0.7 MeV were rejected by considering only the appropriate part of each pulse-height spectrum. The application of pulse-shape discrimination techniques[22] at the detectors eliminated that portion of the background due to gamma rays. The remaining neutron background counting rate was less than 30% of the total counting rate for the various scatterers used. A 40-μA deuteron beam current provided a typical difference counting rate (scatterer in minus scatterer out) of 3 counts/sec. For several of the measurements, NE213 liquid directional detectors[23] of the parallel plate type which allowed for pulse-shape discrimination were used in place of the stilbene crystals. This reduced the background counting rate to 5%. However, in this particular application of the directional detector, the advantage of reduced background was nullified by the lower detection efficiency, inherent in this type of detector, since sufficiently low background was obtained with the stilbene crystals.

The difference in the detection efficiency of the left and right detectors was taken into account by adopting a previously described method[11]: the collimator assembly was mounted on a light table which could be rotated about the target, and the true "left-right" scattering ratio was determined from the relation $r = (r_1 r_2)^{1/2}$, where r_1 and r_2 are the measured ratios at the 50° position of the collimator on each side of the deuteron beam; i.e., $(\theta_1, \Phi_1) = (50°, 0)$ and $(50°, \pi)$. These data were corrected for background by taking additional runs with the scatterer removed. Care was taken with the alignment of the assembly to avoid the introduction of false asymmetries. Alternate measurements were taken with scatterers rotated through 180° about the axis of symmetry for the purpose of eliminating errors due to imperfections in the cast. A plastic scintillator of sufficiently small dimensions (0.1-in. diam×0.1 in.) to permit pulse-height discrimination for gamma rays was used to monitor the neutron flux for comparison of the "scatterer in" and "scatterer out" runs.

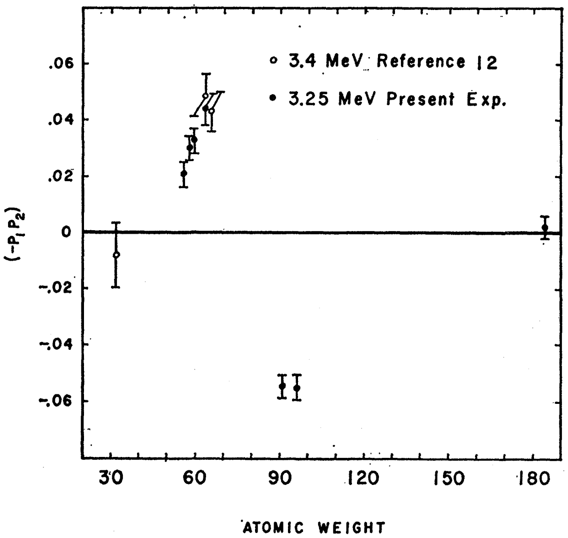

FIG. 3. Experimental neutron polarizations for 90° scattering angle.

RESULTS AND DISCUSSION

The experimental results are presented in Table I. Each value of $(-P_1P_2)$ is the result of a series of measurements. The standard deviation of $(-P_1P_2)$ determined from a comparison of the values obtained from the separate measurements exceeded that inferred from counting statistics only, by a factor of 1.06 on the average. Therefore, the contribution to the total uncertainty due to such possible causes as electronic drifts, unstable monitoring, etc., are very small. The systematic error associated with imperfect alignment of the collimator assembly is estimated to be less than 0.0015.

No corrections have been applied to the results of this experiment. The effect of the finite size of the scatterer and detectors cannot be determined without a knowledge of the angular dependence of the polarization. For the multiple scattering correction a crude estimate yields an increase in the magnitude of the polarization by the following ratios: Fe, 1.28; Ni, 1.21; Co, 1.20; Cu,1.13; Zr, 1.12; Mo, 1.15. Other types of corrections are negligible and need not be considered.

Assuming $P_1 = -0.118$ for this experiment, the results for the polarization P_2 are presented together with the results of other workers in Table II. This value was chosen only to provide a good comparison with the results of Refs. 10 and 12 which assume similar values for P_1. The various results for copper with the exception of that corresponding to Ref. 14 are in reasonable agreement, whereas, for Zr, a large discrepancy exists between the value reported by McCormac *et al.* and those of other workers. The measurements of Ref. 14 include an unknown contribution of inelastically scattered neutrons. It was noted in the present experiment that the polarization for Cu is appreciably lowered if lower channels of the neutron pulse-height spectra are included in

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TABLE II. Comparison of experimental results for $P_2(90°)$.

Element	$E_n=2.8$ MeV[a]	$E_n=3.1$ MeV[b]	$E_n=3.25$ MeV[c]	$E_n=3.3$ MeV[d]	$E_n=3.3$ MeV[e]	$E_n=3.4$ MeV[f]
Mg	$1.00_{-0.13}^{+0}$					
Fe			0.18±0.04			
Ni	0.53±0.25		0.25±0.04			
Co			0.28±0.04			
Cu	0.38±0.15	0.30±0.10	0.37±0.05	0.29±0.50	0.14±0.08	0.42±0.06
Zr		−0.10±0.09	−0.46±0.04		−0.52±0.09	
Mo			−0.48±0.04			
W			0.02±0.04			

[a] Ref. 13.
[b] Ref. 11.
[c] Present experiment: $P_1=-0.118$ is assumed for comparison of the data only (see text).
[d] Ref. 10.
[e] Ref. 14 reports 0.23±0.13 for Cu and −0.77±0.13 for Zr. For the purpose of comparison the corresponding data in the above table follow from $P_1=-0.118$ and are uncorrected for multiple scattering effects.
[f] Ref. 12.

the data analysis. A comparison with the data of Ref. 13 is difficult since conflicting experimental results[17,20,21] allow a wide range of possible values (−0.04 to −0.10) for P_1 to be considered in the energy range used by Iyengar and Peck. $P_1=-0.06$ was chosen by the authors to determine $P_2(90°)$ as given in Table II. However, in view of the high polarization resulting for Mg, $P_2=1.30\pm0.43$ (this value follows from the data of Ref. 13, which presents 1.00_{-13}^{+0} as the final result), and since a multiple scattering correction would appreciably increase all of their reported P_2 values, their experiment seems to support Kane's conclusion[20] that $P_1\approx-0.10$ is applicable for this energy region.

Additional measurements of polarization effects in the elastic scattering of neutrons from carbon were performed during the course of the present experiment. The result, $P_1P_2(45°)=0.101\pm0.005$ (corrected for finite geometry), is to be compared with the calculated value of $\langle P_1P_2\rangle$, which represents an average over the neutron energy spectrum. Using the carbon phase shifts reported by Wills *et al.*,[24] $\langle P_1P_2\rangle=0.056$ is obtained, if for $P_1(E_d)$ a straight line connecting Kane's result to the higher energy, thin-target data of Levintov *et al.* is assumed. Additional calculations which apply to similar measurements by other workers using 3.3-,[25] 3.4-,[12] and 3.5-[9] MeV neutrons were also carried out. In each case the calculated average is approximately 50% lower than the experimental value. Similar results have been obtained by Dubbeldam *et al.*[26] for this energy range. It is noted that if one assumes a larger $D(d,n)He^3$ neutron polarization P_1 which would be consistent with the thick target measurements of Levintov *et al.*, agreement with the phase-shift predictions of Wills *et al.* is still not obtained.

The experimental results for $(-P_1P_2)$ as a function of atomic weight are displayed in Fig. 3 together with the results of measurements at 3.4 MeV reported by Hereford.[12] The 0.7-MeV bias of the detectors was far from sufficient to eliminate the counting of inelastic neutrons in the case of tungsten. Therefore, this value may be appreciably different from that resulting from elastic scattering only. The presence of three isotopes of molybdenum which have levels less than 0.7 MeV is not expected to influence the measurement significantly since comparatively few inelastic neutrons are detected. The data for $A\approx60$ can be represented by a smooth curve; the fluctuations observed[3,4] in this vicinity at lower energies are no longer apparent. Ot-Stavnov and Popov[9] also report a smooth variation of the polarization with atomic weight for $A<64$, using 3.5-MeV neutrons and 30° scattering angle. This might be explained by a reduction of the compound elastic scattering which should also yield larger polarizations. The maximum polarization magnitude reported here (∼0.5) is to be compared with the observed maxima of 0.27 and 0.20 at 2.08 and 0.98 MeV, respectively. The relatively large negative polarization values for Zr and Mo are characteristic of the resonance structure observed[3,4] for 90° scattering angle at lower energies. However, whereas the lower energy data show a pronounced minimum at $A\approx100$ with the polarization tending to small values in the $50\lesssim A\lesssim70$ region, the present data indicate a change in sign of the polarization between $A=70$ and 90 and the attainment of large positive values near $A=65$.

ACKNOWLEDGMENT

The authors wish to thank Walter Taylor for his valuable assistance throughout the course of this work.

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